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Numerical Simulation of Fatigue in Composites

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INTRODUCTION

- The use of composite materials in the marine industry is quite large:
  - High performance crafts.
  - Wind turbines.
  - Tide turbines.
  - Risers, pipelines.

- Importance of the fatigue in naval structures:

DNV-RP-C203

ShipRight FDA

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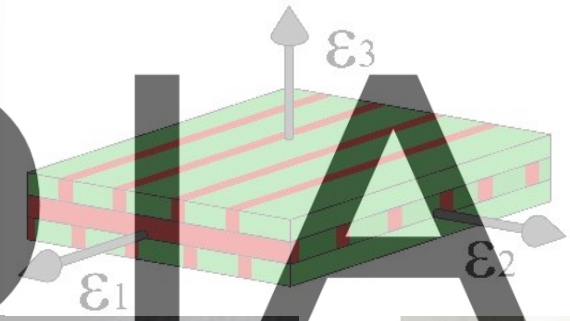
INTRODUCTION

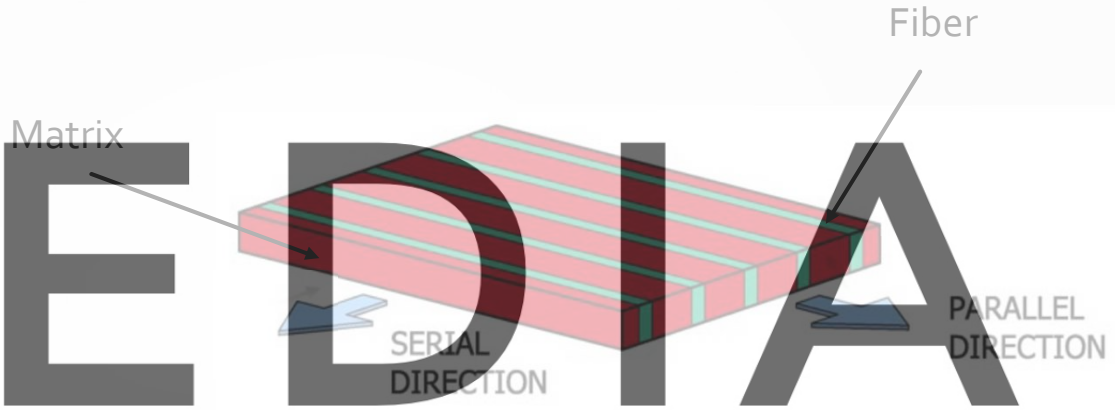
- Challenges:
  - Anisotropic behavior.
  - Prediction of non-linear behavior of composites.
  - Fatigue in composites is still a matter in development: Combined failure modes, range of type of composites, different orientations and lack of data compared with other materials.
- Dealt with:
  - S/P Mixing Theory for non-linear behavior of composites.
  - Fatigue Model based on continuum mechanics.
- Final objective: Prediction of fatigue life for CF/Epoxy cross-ply laminate.
  - CALIBRATION PROCESS



FORMULATION. Serial/Parallel Mixing Theory

Composites

- Constitutive law manager. The method can represent non-linear behavior of composite by means of constituent performance. *Rastellini et al. (2006)*
- Definition of parallel and serial directions:
  - Iso-strain condition for parallel direction.
  - Iso-stress condition for serial direction.
- Implemented and validated on a FEM code.



Parallel behavior

$$\begin{cases} {}^{c}\varepsilon_P = {}^{m}\varepsilon_P = {}^{f}\varepsilon_P \\ {}^{c}\sigma_P = {}^{m}k\,{}^{m}\sigma_P + {}^{f}k\,{}^{f}\sigma_P \end{cases}$$

Serial behavior

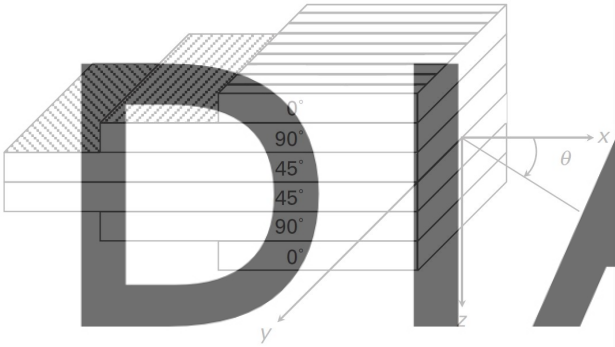
$$\begin{cases} {}^{c}\varepsilon_S = {}^{m}k\,{}^{m}\varepsilon_S + {}^{f}k\,{}^{f}\varepsilon_S \\ {}^{c}\sigma_S = {}^{m}\sigma_S = {}^{f}\sigma_S \end{cases}$$

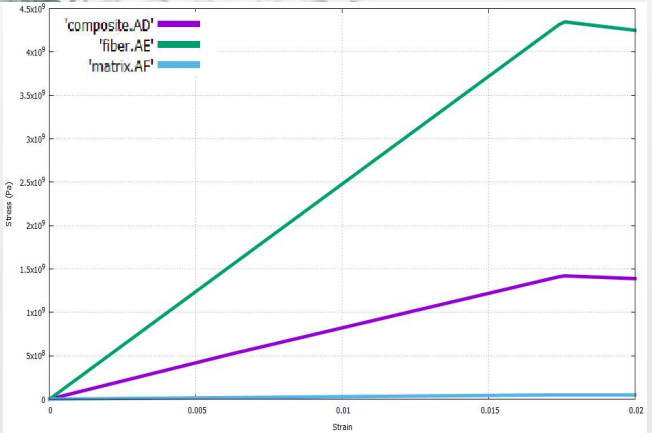
Compatibility equations

FORMULATION. Serial/Parallel Mixing Theory

Advantages

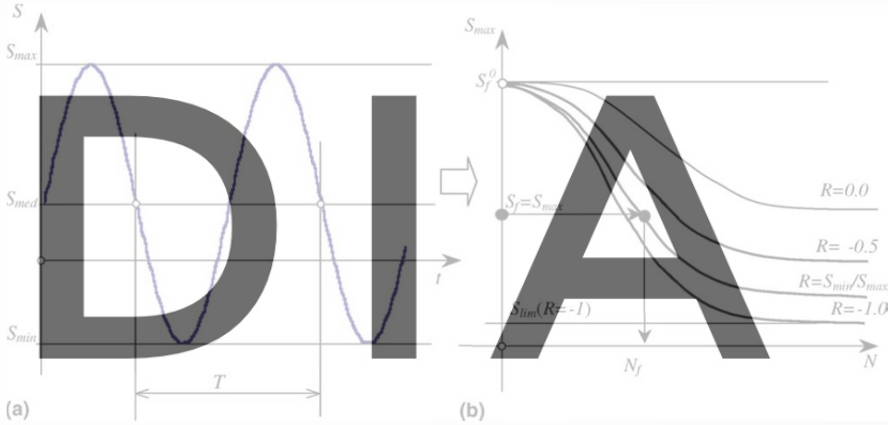
- Any stacking sequence, no matter fiber orientation or fiber volumen fraction.
- Formulation is able to couple different fiber/matrix systems, different constitutive laws.
- Non-linear performance of the composite can be defined from its constituents

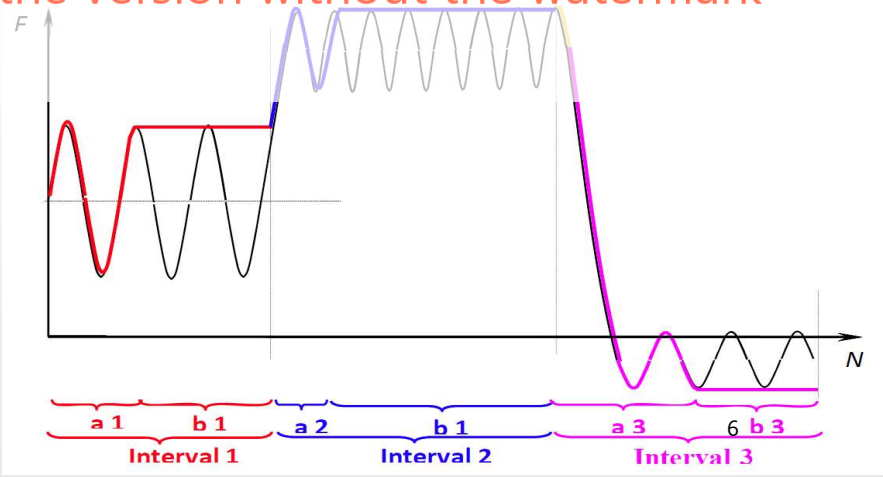




FORMULATION. Fatigue Model

- Fatigue damage formulation by S. Oller.
- Phenomenological model.
- Number of cycles, mean stress and stress ratio effects.
- A reduction function is used to modify the damage threshold.
- Calibration by S/N curves of constituent materials.
- Takes into account different block loading sequence.
- Forward advanced strategy.



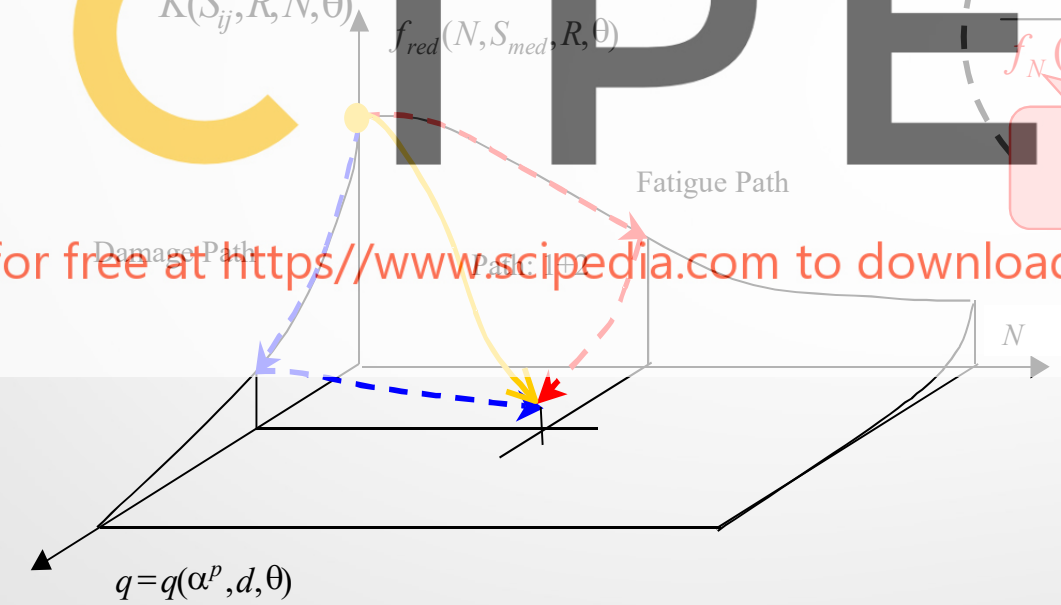


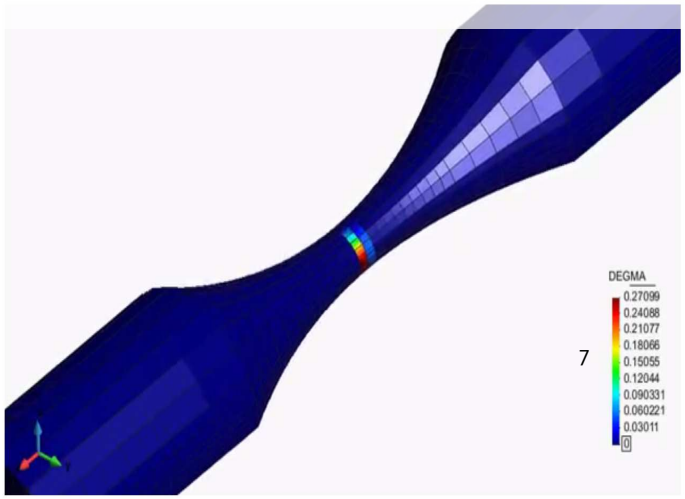
FORMULATION. Fatigue Model

$$\frac{f^P(S_{ij}-\eta_{ij})}{f_N(N,S_{med},R)\cdot f_\theta(\theta)} - \bar{K}^P(S_{ij},\alpha^p) = 0$$

Influence of N_c strength reduction (HCF)

Influence of *Quasi-Static* strength reduction.



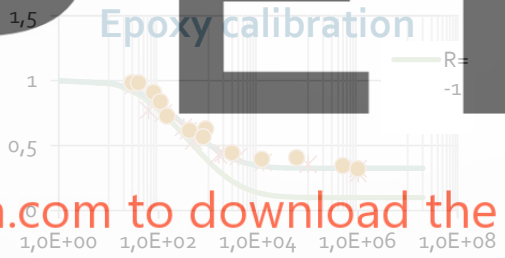


CALIBRATION PROCESS

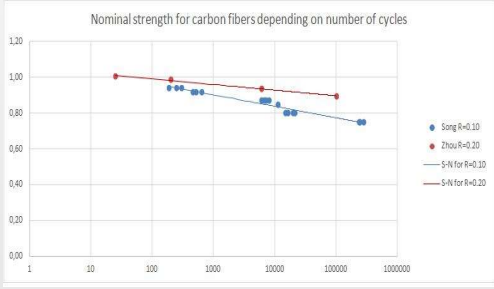
FATIGUE MODELS

Constitutive law for matrix

Epoxy calibration



Constitutive law for fibers



SP MIXING THEORY

Coupling

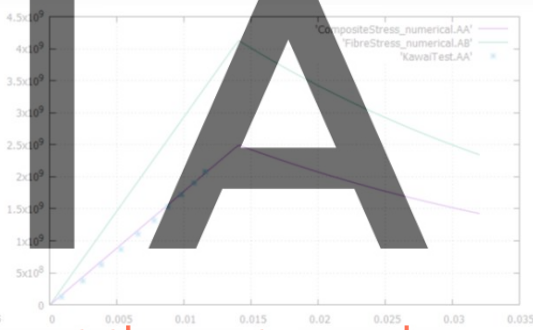
Fatigue behavior of a UD CF/Epoxy laminate

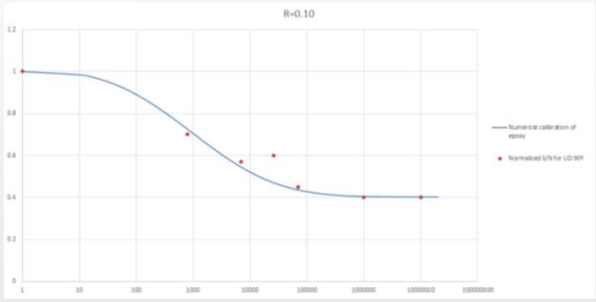
CALIBRATION PROCESS

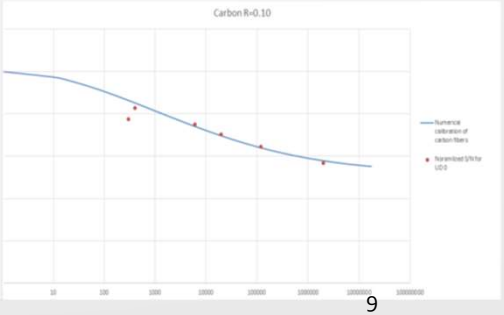
- Requiring to establish fatigue models for fiber and matrix.
- S/P Mixing Theory couples both materials to obtain fatigue behavior of composite.
- Fiber and matrix performance, both static and fatigue, are obtained by UD laminates from Kawai experiments:
  - UD loaded at longitudinal direction has a fiber-dominated performance.
  - UD loaded at transverse direction has a matrix-dominated performance.
- Both hypothesis are in concordance with the formulation used (Serial/Parallel Mixing Theory)
- Failure of the cross-ply laminate is supposed when damage appears on fibers for longitudinal ply.

Matrix

Fiber



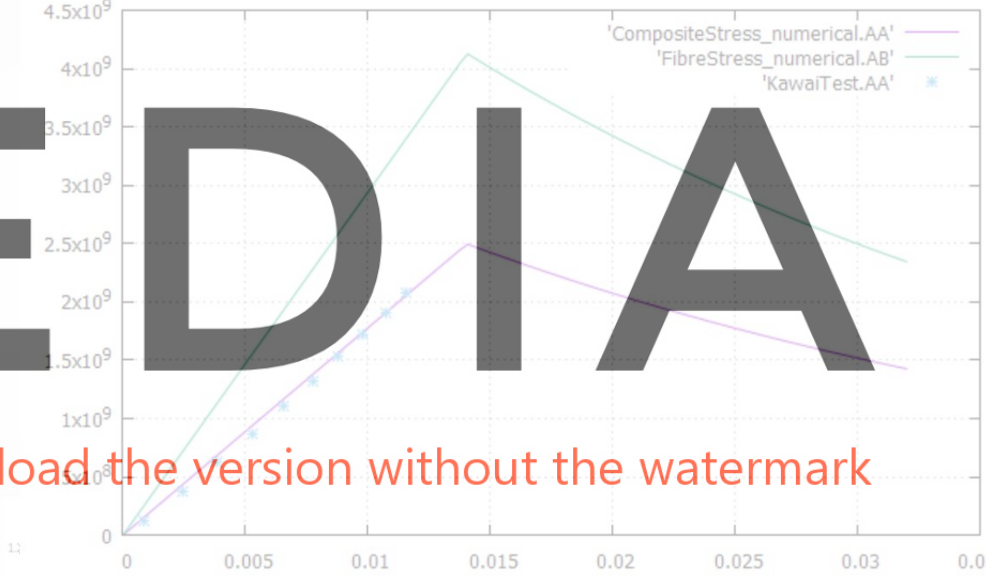


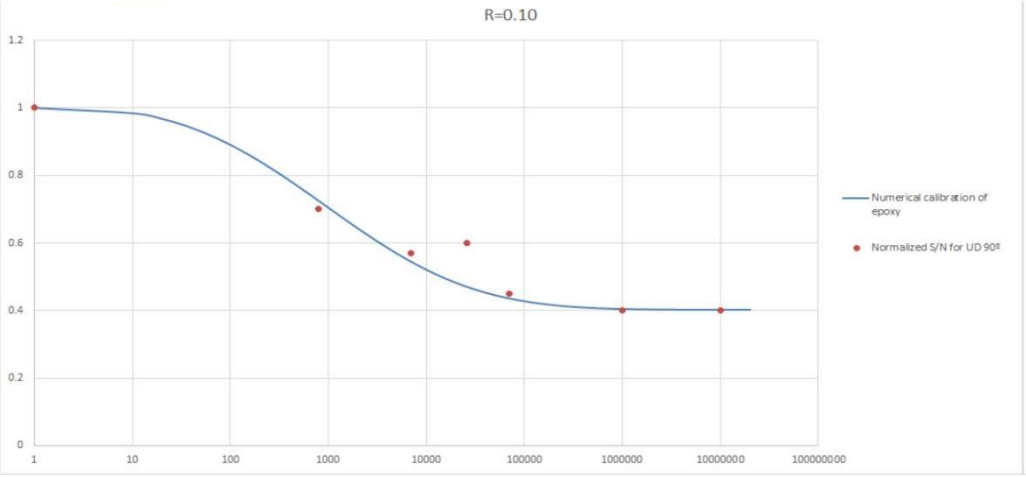


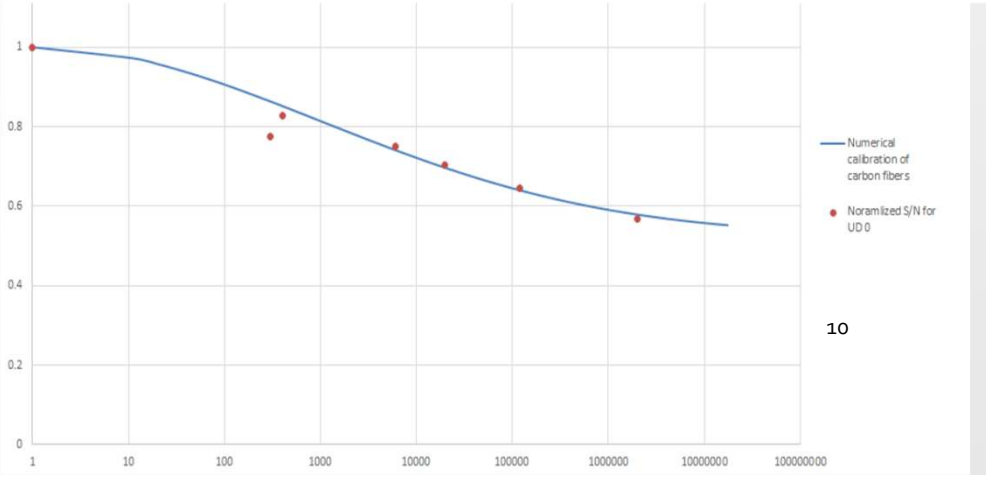
CALIBRATION PROCESS

Matrix

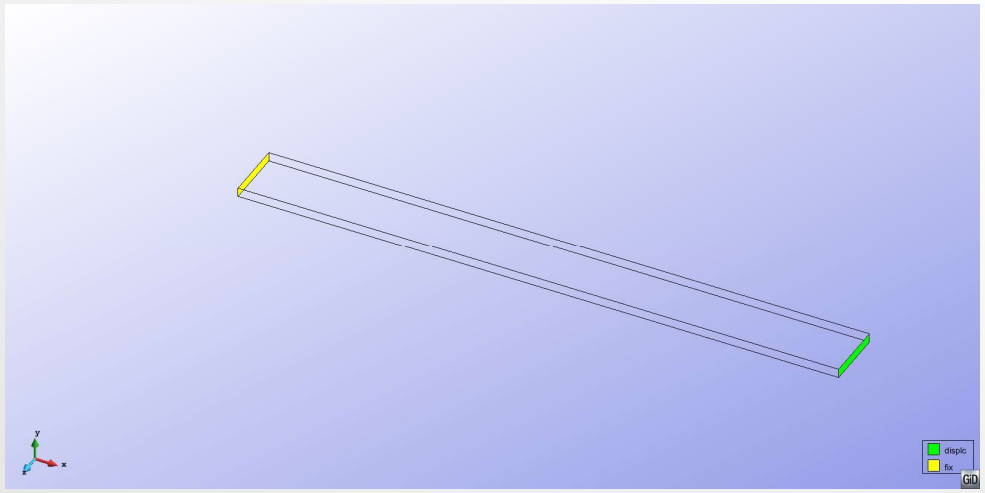
Fiber

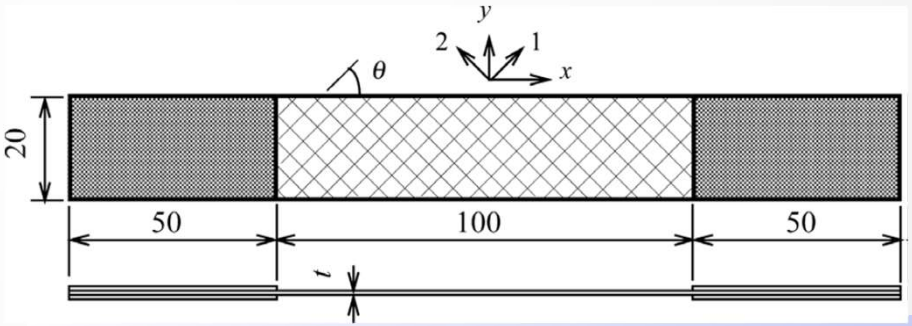


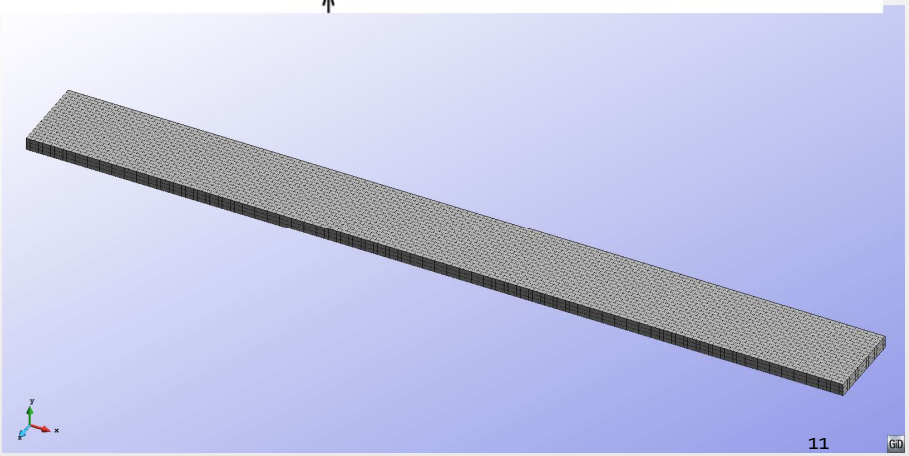




RESULTS. FEM model



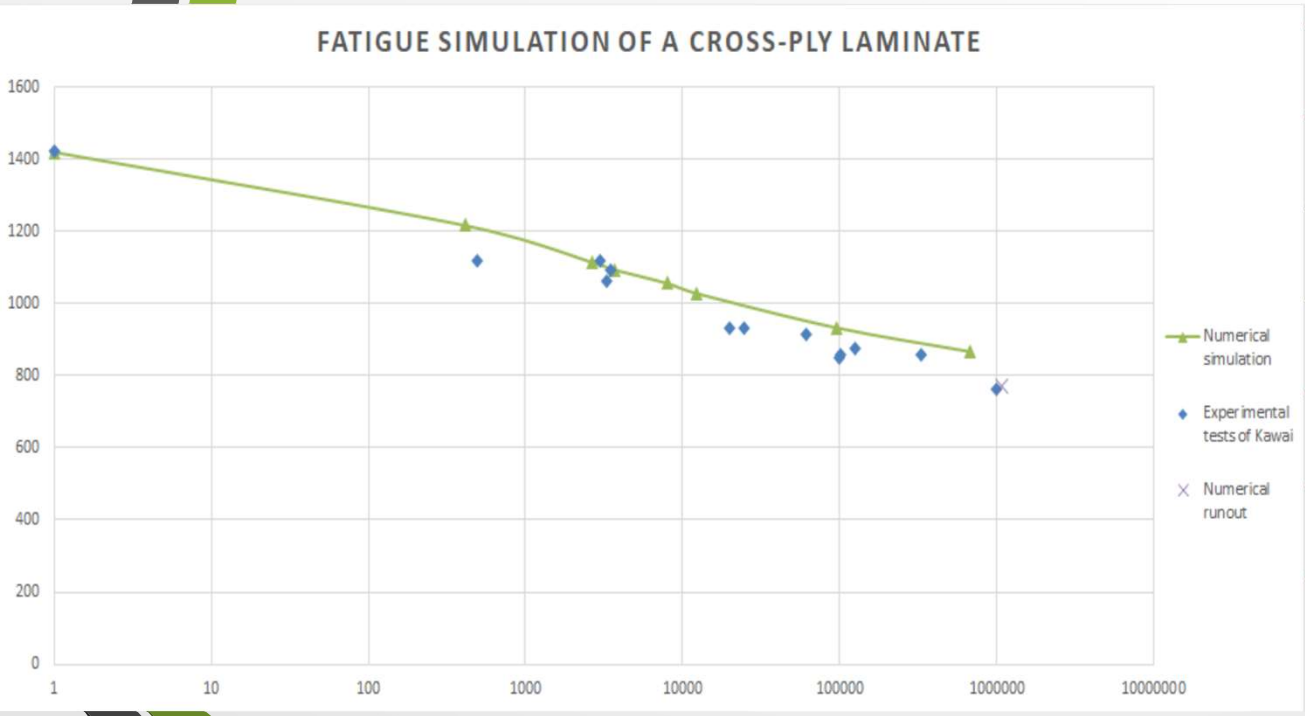




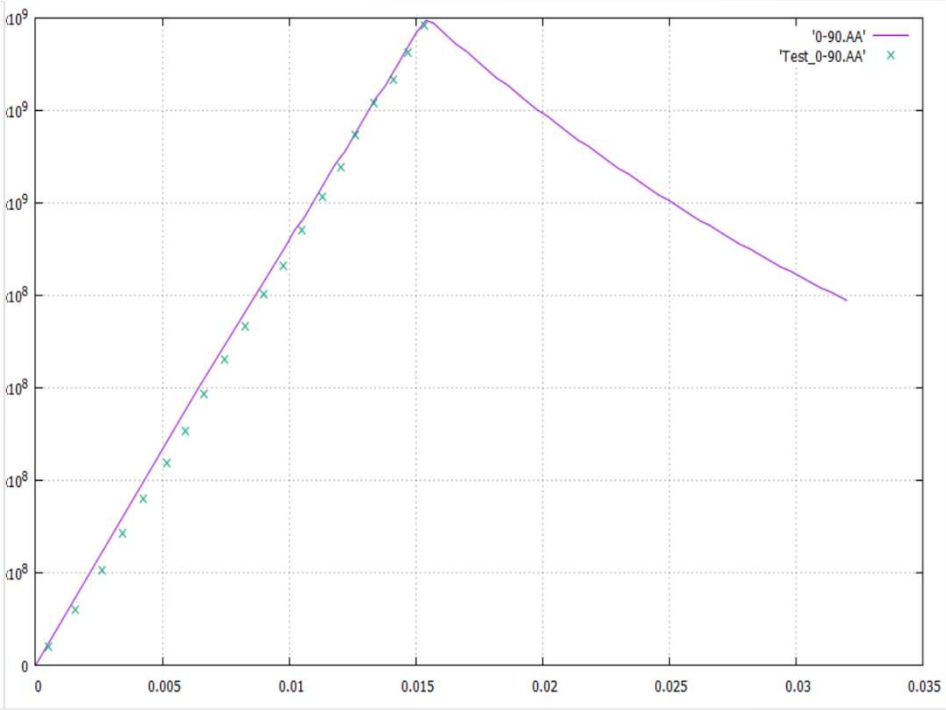
SIZE = 0.75mm , nº elements 13.330, linear elements

RESULTS

Fatigue

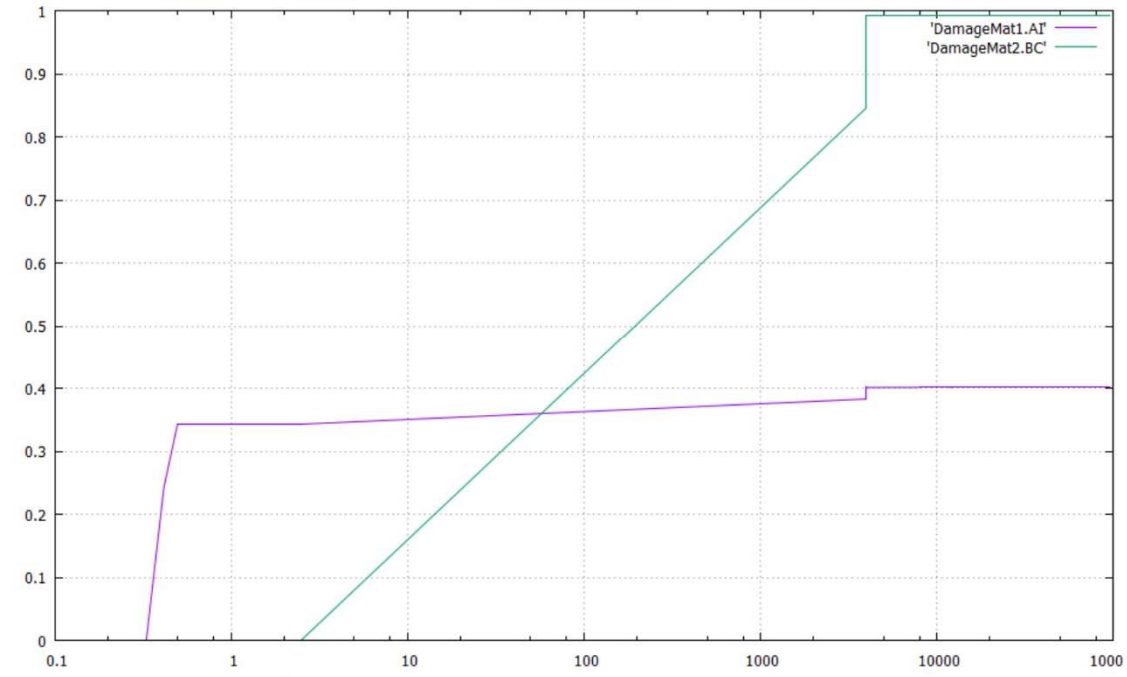


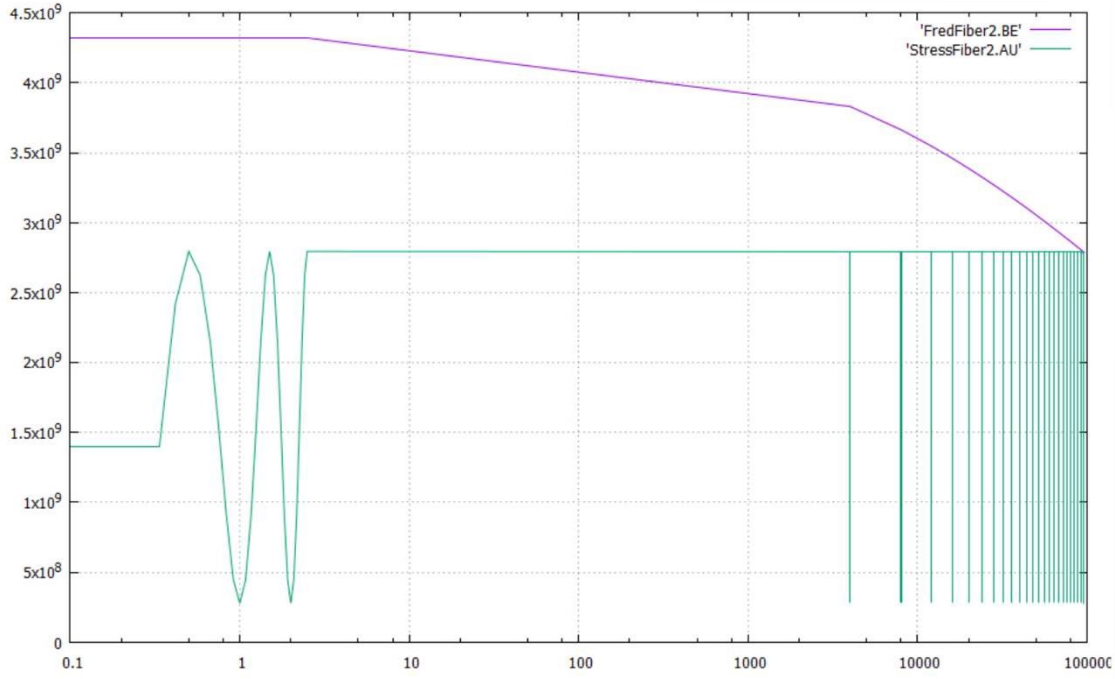
Static



RESULTS

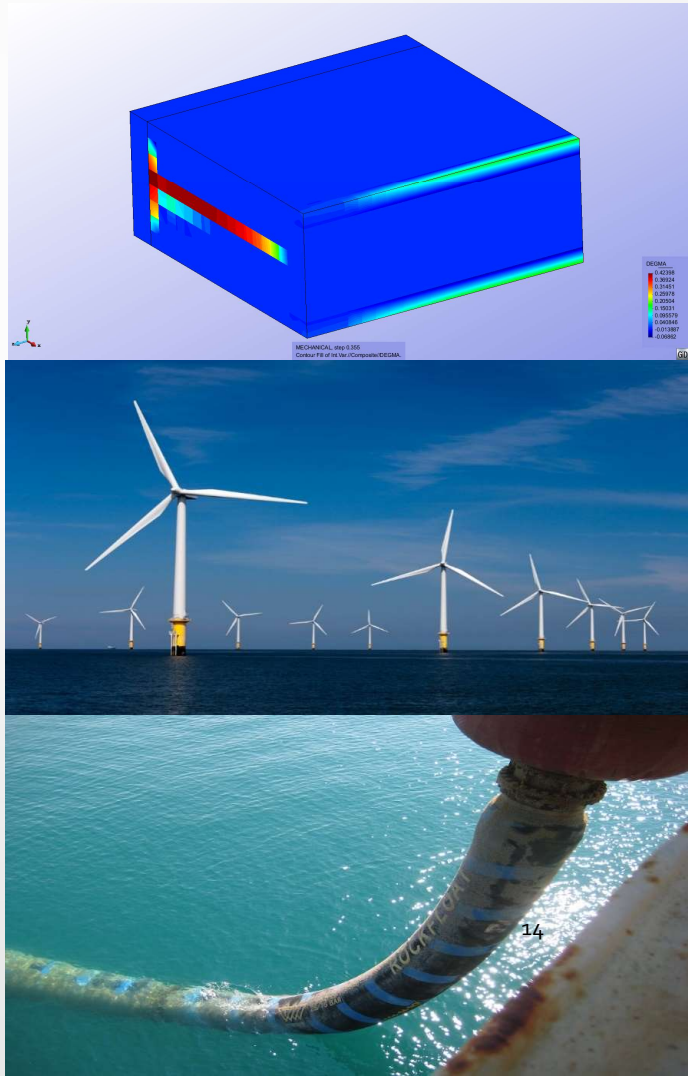
Model allows to follow the damage evolution and observe the failure modes, as delamination, transverse matrix cracking or fiber breaking.





CONCLUSIONS

- RELEVANT ASPECTS
  - Composite fatigue performance is obtained by means of fiber and matrix behavior, regardless fiber orientation or fiber participation, what reduces number of tests to be done
  - Failure modes of the composite can be obtained.
  - S/P Mixing Theory is compatible with known failure criteria (Tsai-Hi, first ply failure, etc).
- APPLICATIONS
  - Wind/tide turbines, composite risers, composite ships.
  - Better understanding of fatigue performance of composite structures.
  - Reduction of uncertainty means structure optimization.
- FUTURE WORK:
  - Taking account fatigue performance for off-axes laminates.
  - Extension to other fiber/matrix systems.



THANKS FOR YOUR ATTENTION

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